

R=100,000 Mid-IR Spectroscopy of UCHII Regions: High Resolution is Worth it!

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Abstract. Ultracompact HII regions are signposts of massive star formation and their properties provide diagnostics for the characteristics of very young O stars embedded in molecular clouds. While radio observations have given us a good picture of the morphology of these regions, they have not provided clear information about the kinematics. Using high spectral resolution observations of the $12.8\mu\text{m}$ [NeII] line, it has been possible for the first time to trace the internal kinematics of several ultracompact HII regions. We find that the motions in the cometary ultracompact HII regions MonR2 and G29.96-0.02 are highly organized. The velocity patterns are consistent with parabolic ionized flows along a neutral boundary layer.

1 Introduction

An understanding of the formation of massive stars and of the effects of these stars on their environments is critical to an understanding of star formation overall. Most stars of all masses form in clusters containing massive stars [5]. High mass stars and the regions of the ISM that they excite are what we use to trace star formation in other galaxies. The formation of massive stars ultimately destroys the star forming clouds.

Ultracompact HII (UCHII) regions are one of the earliest manifestations of massive stars. High extinction and substantial emission by overlying dust make it impossible to detect the photospheres of very young O stars directly at any wavelength. The UCHII regions, however, become detectable in the radio continuum and in mid-IR fine-structure lines while young O stars are still embedded in their natal envelopes, as soon as the stars have begun to emit any significant amount of Lyman continuum radiation.

We have been using the $12.8\mu\text{m}$ fine-structure line of [NeII] to study the morphology and kinematics of a sample of UCHII regions. Our ultimate goal is to understand the natures of the regions and how they depend on the age and mass of the exciting star, as well as on the properties of any disk or envelope. We would also like to learn how long the UCHII regions last and how the evolution of these regions affects the surrounding cloud. In this paper, we summarize results from our initial studies of UCHII regions with an apparently cometary morphology [3] [10].

2 Observations

Radio recombination line observations, even when made with aperture synthesis instruments with high spatial resolution, have not been able to reveal the kinematics of UCHII regions in detail. In at least some UCHII regions, radio observers have been able to find evidence for a mix of broad and narrow hydrogen recombination line components [1], for systematic velocity gradients [2] [7], and for multiple velocity components. In this section, we describe the observations we have made with the TEXES spectrometer [4] at the IRTF and the advantages these observations have over radio recombination line results.

Over the past few years, we have mapped a small sample of UCHII regions using the mid-IR spectrometer, TEXES on the NASA IRTF in the $12.8\mu\text{m}$ fine structure line of [NeII]. TEXES has sufficiently good spectral resolution (3.4 km s^{-1} at $12.8\mu\text{m}$) to be able to resolve structure in the shapes of the nebular emission lines. With a $1.4''$ slit, the TEXES-IRTF combination has a spatial resolution that compares favorably with that of most existing VLA maps of radio recombination lines. We have mapped our sample of UCHII regions by scanning the TEXES slit (while holding the telescope secondary fixed) across the sources and adjacent blank sky. At the high spectral resolution of TEXES, it is then possible to produce accurate maps of the [NeII] intensity distribution by subtracting the average off-source spectrum from the spectrum at each point where emission may be present.

Two of the main advantages of observing UCHII regions in the mid-IR derive from properties of the [NeII] line rather than of the instrument. The first of these is that the line is incredibly bright. Our observations of Mon R2, show a ratio of [NeII] line flux to 5 GHz radio continuum flux density of $1.5 \times 10^{-13} \text{ W m}^{-2} \text{ Jy}^{-1}$ making it possible to obtain $S/N \sim 50$ spectra of narrow lines with TEXES in only 10 seconds of integration in regions with radio continuum flux densities of only 10 mJy per beam [3]. The other advantage derives from neon's large atomic weight. In gas where the motions are entirely thermal, the neon line will be only 22% the width of a hydrogen recombination line. The much smaller thermal widths allow neon spectra, when observed at the high resolution possible with TEXES, to reveal mass motions at much lower levels than is possible with hydrogen line observations. Figure 1 shows a [NeII] spectrum toward one position in the MonR2 UCHII region[3]. Superposed on the observed spectrum is a model showing what an observation of the same region in a hydrogen recombination line would have looked like. The thermal broadening of the hydrogen line completely masks the complex structure apparent in the [NeII] observations.

3 Progress Report

In our first paper on TEXES mapping of [NeII] emission from UCHII regions, we described observations of Mon R2 [3]. The two remarkable results in these measurements were (1) that the lines were locally quite narrow (as small as 8 km s^{-1} FWHM) and (2) the velocity structure of the region was predominantly

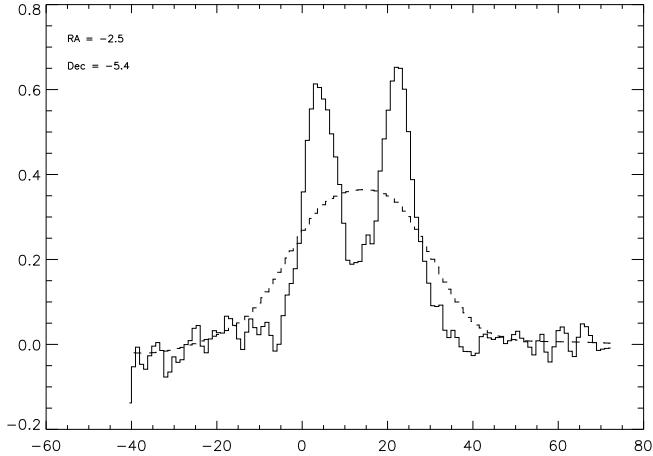


Fig. 1. [NeII] spectrum toward the interior of MonR2. The solid line shows the spectrum at full resolution ($\Delta V = 3.4 \text{ km s}^{-1}$). The dashed line shows the same spectrum smoothed with a 20 km s^{-1} Gaussian (the thermal broadening of hydrogen lines at 10^4 K , or the resolution of a resolving power 15,000 spectrometer).

in the form of large-scale and well-organized features. These features did not, however, fit the simple pattern of an outflow or an expanding shell.

Both Mon R2 and the second region we have analyzed in detail, G29.96-0.02 [10], have a cometary morphology, a characteristic they share with roughly 20% of all UCHII regions [9]. Over the past 15 years, a number of authors have modeled cometary UCHII regions as flowing ionized gas behind a bow shock. In the models, the ionizing O star has a peculiar velocity with respect to its parent cloud. The bow shock forms at the interface of the high velocity stellar wind and the dense molecular gas flowing toward the star. Numerical simulations have been compared in detail to the radio continuum morphologies of cometary UCHII regions [6]. More recently, an analytic model, including at least some of the relevant physics has been developed [8].

The more detailed kinematic information made available by the high signal to noise and low intrinsic line widths of the [NeII] line makes possible a more detailed comparison of UCHII region motions to the parabolic flows predicted by bow shock models. In Zhu et al. [10], we compare [NeII] mapping of both Mon R2 and G29.96-0.02 to such a parabolic flow picture. We have developed a simple numerical model to predict the kinematics in cometary UCHII regions resulting from the interaction of the stellar wind and the inflowing molecular gas in the bow shock. The model accounts for the ionization equilibrium, momentum flow, and pressure differentials in the ionized parabolic shell [10]. Figure 2 shows how the gas flows along the shell that forms at the boundary between the fast stellar wind and the moving (in the frame of the star) molecular gas.

A comparison of models and observations shows that the fairly simple parabolic flow pattern produced by the bow shock models describes the UCHII regions

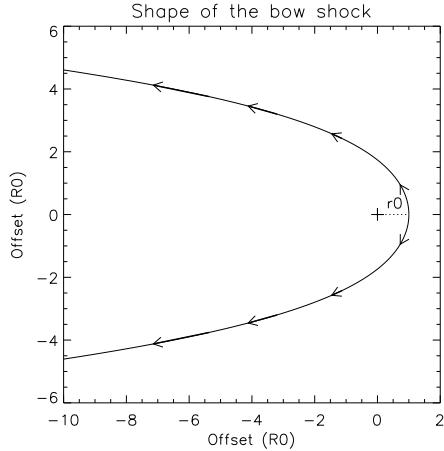


Fig. 2. Calculated shape and velocity field of a bow shock for the model that best fits G29.96-0.02 [10]. The cross at (0,0) shows the position of the exciting star and the arrows show the velocity of the flowing gas in the frame of the star.

very well. Zhu et al. [10] will discuss the issues involved in the physics of the regions. Here we simply point out the observational fact of the remarkably good agreement between the data and the models.

Figure 3 compares, in succeeding panels, position-velocity diagrams for a parabolic flow model and p-v diagrams of G29.96-0.02 itself. Cuts both parallel and perpendicular to the symmetry axis show remarkable similarity when one compares the data and the model at the corresponding points within the structure.

4 Future Directions

While the close match of the bow shock models and the observed kinematics of Mon R2 and G29.96-0.02 is extremely encouraging, it marks more of a beginning than an end to our investigation of the nature of UCHII regions. The close match between models and observations says that the kinematic part of the models is likely correct; any picture of cometary HII regions must produce a systematic flow along a relatively thin, approximately paraboloidal shell. The high frequency of cometary UCHII regions and the large peculiar stellar velocities we need in our fits, however, argue that we have not yet produced a complete description of the physics of the fluid flow. Zhu et al. [10] discuss some of the issues involved and our group continues work on more elaborate hydrodynamical models. The bow shock picture, in any case, can explain neither all of the features observed in the two sources discussed here (in particular, the compact, jet-like feature in Mon R2 [3]) nor the general kinematics of sources with non-cometary morphologies. A combination of more detailed hydrodynamic modeling and the higher spatial

resolution afforded by 8m class infrared telescopes will make it possible for us to get at the causes of the large-scale motions in these other classes of sources.

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References

1. De Pree, C.G., Wilner, D.J., Mercer, A.R., Davis, L.E., Goss, W.M. & Kurtz, S.: ApJ, 600, 286 (2004)
2. Garay, G., Rodriguez, L.F., & van Gorkom, J.H.: ApJ, 309, 553 (1986)
3. Jaffe, D.T., Zhu, Q., Richter, M.J., & Lacy, J.H.: ApJ 596, 1053 (2003)
4. Lacy, J.H., Richter, M.J., Greathouse, T.K., Jaffe, D.T., & Zhu, Q.: PASP, 114, 153 (2002)
5. Lada,C. & Lada, E.A.: ARAA, 66 (2003)
6. Mac Low, M.M., van Buren, D., & Churchwell, E.: ApJ 369, 395 (1991)
7. Tieftrunk, A.R., Gaume, R.A., Claussen, M.J., Wilson, T.L., & Johnston, K.J., A&A, 318, 931 (1997)
8. Wilkin, F.P.: ApJ, 459, L31 (1996)
9. Wood, D.O.S., & Churchwell E.: ApJS 69, 831 (1989)
10. Zhu, Q., Lacy, J.H., Jaffe, D.T., Greathouse, T., & Richter, M.J.: in preparation (2004)

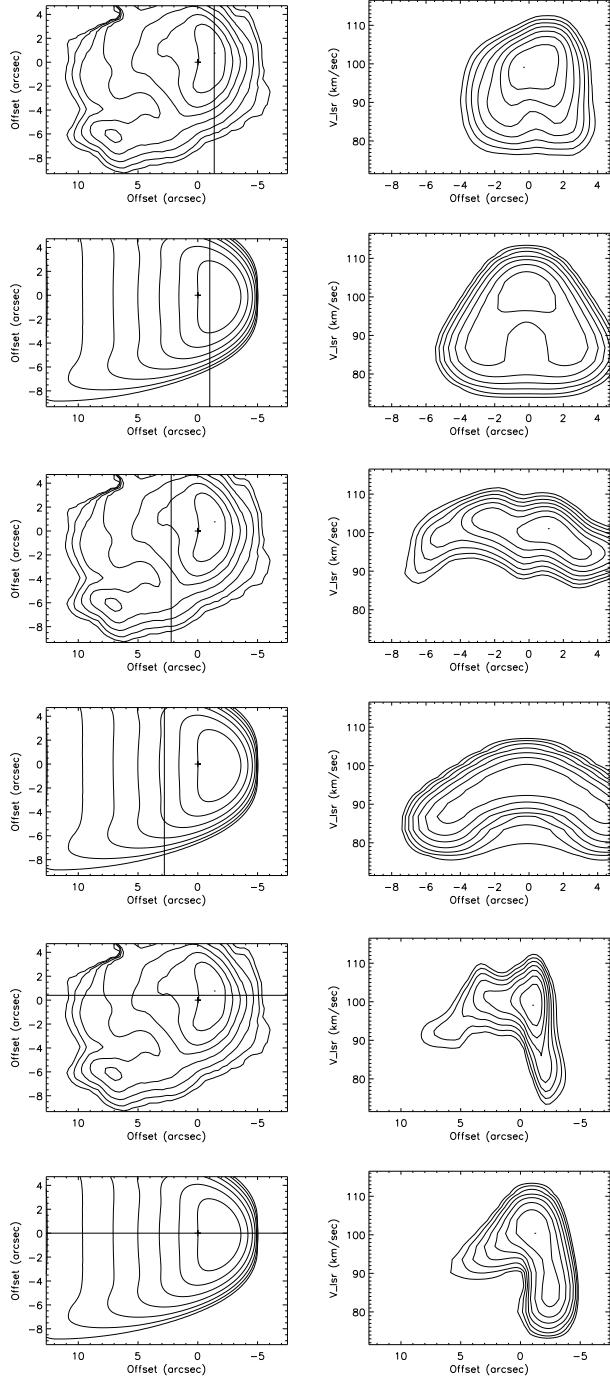


Fig. 3. The left column shows alternately [NeII] integrated linestrength maps toward G29.96-0.02 [10] and integrated line representations of a bow shock model for this source, in each case with a superposed line showing the location of the position-velocity diagram shown to the right of each map. For all three p-v cuts, the observed and model diagrams are remarkably similar.